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On FAME's Star Transit Rate

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ABSTRACT

The effects of Galactic structure on FAME's "star" transit rate (STR) is investigated. The STR is defined as the number of "stars" that are detected, per second. For the purpose of this memo, a $m_V \leq 9^{th}$ magnitude star is counted as 20 "stars," to accommodate the extra cross-scan data. These calculations are made with modified versions of a set of IDL programs by Scott Horner and employ the USNO-A2 catalog to determine the local stellar number densities. The STR is calculated for three models of various resolution. The highest STRs are easily recognized and occur when both apertures scan through the Galactic plane (GP) for long periods of time. The maximum simulated STRs are of order 12,000 "stars" per second when FAME's spin axis points towards a Galactic pole. Such Galactic plane rolls (GPRs) are spaced by about a precession period and last about 9 days each. A typical year contains 14 GPRs as compared to 18 precession periods. An on-board data buffer of 1 to 2 Gbit is sufficient to handle Galactic plane (GP) crossings outside the GPR periods. However, this buffers is two orders of magnitude smaller than the number of stars accumulated during a GPR. Due to the concentration of FAME target stars towards the Galactic plane, more than 50% of the astrometric observations would be scheduled at times that the average STR exceeds the CSR down-link rate of 822 stars per second. This percentage decreases to about 17% if the maximum down-link rate equals twice the CSR rate. The mission-total percentage of observations lost equals 19% (4%) for a down-link rate of 822 (1644) stars/second. These percentages are significantly larger (35.6% and 23.6%) in high-density (Galactic plane) regions.

1. Introduction

From the USNO-A2 catalog, star counts were compiled on a grid in Galactic coordinates, where the cell boundaries are X degree apart (in l and b). For each of the FAME apertures locations[1], the local stellar densities are determined from the star-count table and the $1/\cos b$ correction factor. The star-rate equals the product of the local stellar density, the surface area of FAME's CCDs (24x0.02746=0.659 sq.deg), and the read-out frequency (1/1.56 seconds^{-1}). For each time-step, these values are stored in arrays for future analysis and plotting.

In the highest resolution model, the bin-size X equals 0.2°, the observing span equals 120 days, and is split up in 1 second intervals. For the intermediate and low resolution models, $X = 1°$, the time steps are 1 and 5 seconds, and the mission durations are 1 and 5 years, respectively. For the two low resolution models, I place *both* apertures on the sky, determine the center of the apertures and determine the local stellar density assuming a single detector of 0.659 square degrees area. In the high resolution model, I position each CCD separately, so that the star transit rate (STR) equals the sum of the CCD-specific STRs. Thus, less smoothing is applied in the high-resolution model, and the peak STRs are about twice as large as in the low-resolution models (12,000 versus 6,000). The real, unsmoothed maximum data rate may still be larger. I am currently implementing a completely unsmoothed version of the simulator.

Table 1: Model properties. Tabulated are: resolution (1^{st} column), grid size (2^{nd}), time step (3^{rd}), scan step (4^{th}), mission duration (5^{th}) and number of samples (6^{th}).

resolution	grid size	τ_{step}	$\delta\psi$	$\tau_{mission}$	$N_{samples}$
high	0.2°	1 sec	0°.15	120 days	10.4 10^6
medium	1.0°	5	0°.75	1 year	6.3 10^6
low	1.0°	25	3°.75	5 years	6.3 10^6

The STR is split up in three parts: 1) stars brighter than $m_R < 9$ (bright stars), 2) stars with $9 \leq m_R < 15$ (FAME stars), and 3) stars with $15 \leq m_R < 16$ (FAME$^+$ stars). With these USNO-A2 red magnitudes limits, these groups comprise 199,514, 42,365,500 and 46,712,200 stars, respectively[2]. Taking the 2D nature of the postage stamps for bright stars into account, I assume that the STR for the bright stars is twenty times larger than the rate at which real stars transit the aperture. Also, the STR is normalized to a total of 40 million stars.

[1]The aperture motion includes: S/C spin, precession(20 days) and the Earth's orbital motion. The Sun angle equals 45°.

[2]In the remainder of this memo I will not discuss the FAME$^+$ stars explicitly. Because there are a similar number of FAME and FAME$^+$ stars, $STR_{FAME^+} \approx STR_{FAME}$.

2. Results

Figure 1 shows the STR for a period of one day outside the GPR season (high-res model). Star rates go up to 2600/sec during plane crossings, and reach quite low levels at high latitude. The next-1Gbit average (N1GBA[3]) rate (black wiggly line) hovers around the nominal down-link rate (DLR, [orange]): this is an average day in the life of FAME. Experimenting with the size of the buffer has no appreciable effect: as long as the buffer is so large that it can accommodate the observations accumulated during a GP crossing, the maximum data rate is (just) large enough to send all observations to Blossom Point. Astrometric observations are lost when the N1GBA down-link rate exceeds the nominal DLR. There are several ways how to characterize the severity of these situations. I include the following:

- the time spent in high-density regions ($\tau_{N1GBA>DLR}$)
- the potential number of observations in high-density regions ($N_{N1GBA>DLR}$)
- the fraction of observations lost in high-density regions ($N^{lost}_{N1GBA>DLR}$)
- the fraction of mission-total observations lost (N^{lost}_{tot})

For the 1-day period shown in figure 1, the N1GBA rate exceeds the down-link capacity during 50.8% of the grand-total observing time. The number of stars observed during those periods comprise 52.0% of the total number of observations. However, only 1.3% of the total number of stars present in the high N1GBA regions are lost. The percentage of the grand-total of the observations during this day is only 2.4%. The fraction of unobserved stars is small because the N1GBA rate exceeds the DLR in regions of *low instantaneous STRs* (see below).

In this particular example of data buffering and scheduling of observations, stars in the GP will always be observed, while the buffer is “full” during the high latitude parts of the scans. That is to say, by the time that an aperture hits the GP, there is plenty of room in the buffer which will be filled up rapidly. On this day, stars that are lost are found at intermediate latitudes. This is clear from figure 1: the N1GBA rate exceeds the DLR *in between* GP crossings (at low instantaneous STRs).

[3]This rate follows from the time it takes FAME to accumulate 1 Gbit worth of future measurements, or 2.976 10^6 stars stars at 336 bits per star. At a DLR of 822 sec^{-1}, it takes about one hour to accumulate 3 million stars.

For buffer sizes $\lesssim 3\ \frac{N_{FAME}}{40 10^6}\frac{822}{DLR}$ million stars, the details of the exact buffer length and the Galactic longitude of the GP crossing determine whether or not the peaks of the N1GBA line up with the peaks of the instantaneous STR. Preliminary investigations show that such problems hardly occur for a twice larger buffer. If it so happens that a "buffer-full" condition occurs during a scan through a high-density region, the number of astrometric observations lost is significantly larger. The extreme case of such a situation is discussed in the next section.

2.1. Galactic Plane Rolls

As mentioned in the Abstract, 14 out of 18 precession periods have a scanning law that takes the path of the apertures to within a few degrees from the Galactic plane. In figure 2, I present the one-year STR plot obtained from the intermediate-resolution model. The low resolution plot for a 5 year mission duration is very similar to the 1-year plot, and is hence not presented. In these figures the GPRs are clearly identified as the high STR peaks.

For reference, I present close-ups of the GPR event around day 99 in figures 3 and 4. For the purpose of this document, I define a GPR as any contiguous period in which the next-1Gb-averaged STR exceeds the nominal down-link rate. Figure 3 shows that this GPR lasts about 9 days. The duration of the GPRs decreases with increasing DLR (to about 2 days for 1844 stars/sec). About 54% of the mission-total number of observations would be scheduled during GPR periods. In fact, one has to abandon $\sim$ 68% of possible stellar observations during the most unfavorable GPRs (35% for the average GPR).

The various different parameterizations listed in the previous section are tabulated in table 2. The numbers in column 6 show that the percentage of time that the average data-rate exceeds the down-link rate decreases steadily with increasing DLR, as expected. Also, the number of astrometric observations during high average STRs (column 7) decreases substantially, but not as quickly as the time lingered on high density regions: this indicates that the N1GBA rate is dominated by periods of large stellar densities. The fraction of the mission-total number of astrometric observations that are lost (column 9) decreases steadily with increasing DLR, in part due to the narrowing of the regions where the N1GBA rate exceeds the maximum DLR (only 2 days for $\mathrm{DLR}_{mul} = 2$). On the other hand, increasing the data-rate hardly helps those stars that are found in the highest density regions: the $P^{lost}_{N1GBA>DLR}$ numbers decrease only slowly with DLR (column 8). However, with the data-rates considered here, only a relatively small fraction of the high-density stars are lost (16-36%). Recuperating *all* the stars in high-density regions would require DLRs of order 6,000 stars per second.

Table 2: A tabulation of the effects of increasing the nominal down-link rate (NDLR, 4^{th} column) by a multiplicative factor (DLR_{mul}, 5^{th} column). The first three columns describe the model parameters: mission time (days), time step (seconds) and input catalog size (10^6), respectively. The last four columns represent: (6) the percentage of the mission time spent in regions where the N1GBA rate exceeds the maximum down-link rate ($\tau_{1GBA>DLR}$), (7) the percentage of the mission-total number of observations made during high N1GBA rates, (8) the percentage of observations lost during high N1GBA rates (9) the percentage lost of the mission-total number of observations. These numbers are for the intermediate resolution model: the other models yield similar values.

$\tau_{M,days}$	$\tau_{S,sec}$	$N_{tot,6}$	NDLR	DLR_{mul}	$\tau_{N1GBA>DLR}$	$P_{N1GBA>DLR}$	$P^{lost}_{N1GBA>DLR}$	P^{lost}_{tot}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
365.25	5	40	822	1.00	39.47	54.30	35.61	19.34
365.25	5	40	822	1.20	24.50	39.98	34.85	13.93
365.25	5	40	822	1.40	16.98	31.43	33.00	10.37
365.25	5	40	822	1.60	12.58	25.59	30.36	7.77
365.25	5	40	822	1.80	9.87	21.53	26.90	5.79
365.25	5	40	822	2.00	7.76	17.98	23.55	4.23
365.25	5	40	822	2.20	5.78	14.31	21.24	3.04
365.25	5	40	822	2.40	4.27	11.23	19.18	2.15
365.25	5	40	822	2.60	3.05	8.53	17.68	1.51
365.25	5	40	822	2.80	2.08	6.21	17.00	1.06
365.25	5	40	822	3.00	1.42	4.53	16.59	0.75

The logic I have applied to decide which stars are and which stars are not observed is rather primitive. Thus, the fractions quoted in table 2 serve as “reasonable” indicators of the severity of the effects of large stellar transit rates on the completeness of our final catalog.

How we can ensure that all Galactic plane targets will be observed more-or-less the same number of times? Table 2 shows that at 822 sec^{-1}, 1 out of 3 stars must be skipped in GPRs. Following Sean Urban’s suggestion, one could assign GP stars a GPR-flag (GPRF=1,2 or 3). During the 1^{th} GPR, GPRF=1 stars will be skipped, during the 2^{nd} GPR, GPRF=2 stars will be skipped, et cetera. This scheme requires the counting of GPRs, which could be determined before hand on the ground and uplinked, or from a counter that keeps track of the Galactic latitude of the pole of the spin axis.

2.2. Additional Correlations

In figure 5 I plot the instantaneous STR (black dots; left-most axis) together with the galactic latitude of the position of FAME's spin axis (red dashed line). This figure confirms the assertion that high STRs cur when the spin pole comes to within 20°of the Galactic pole. Also note that high instantaneous rates occur outside GPR seasons when the apertures plow through the Galactic center or other regions of high stellar densities.

I also accumulated various statistics on a day-by day basis. The maximum, the average and minimum STRs attained during periods of 1 day are plotted in figure 6 (high-res model). Again, note that the peak STR can be as large as 12,000 sec^{-1}, and that the average STR during a GPR is well above the nominal down-link rate. Finally, even during GPRs, the minimum STRs are of order 500 stars/second.

3. Data Volume Considerations

The CSR number of 336 bits per star seems very large considering that only 120 bits (10 pixels times 12 bits/pixel) are required for the intensity data. How many bits do we really need per star? I will only consider the 1-D data as the 2-D data rate is only a small fraction of the STR (fig. 1). The number of bits per 1-D postage stamp is determined from the following enumeration:

- 1) 120 bits for the intensity values
- 2) 2 bits for the gain setting of the A/D converter
- 3) 6 bits for the 48 CCD identifiers
- 4) 10 bits for the start CCD column number
- 5) 4 bits for the number of cross-scan pixels average
- 6) 34 bits for the time stamp
- 7) (16 bits for the Input catalog box number [$B_{IC} \leq 65536$])
- 8) (16 bits for the star number within the box [$N_B \leq 65536$])

- 9) (4 bits for a data-format identifier[4])

Items 1 through 6 add up to 176 bits, or 1.9 times smaller than the CSR number. Thus, a larger down-link rate in terms of stars sec^{-1} seems feasible. That would also allow for an increase in the total number of stars observed.

The number of bits for the time-stamp information is arrived at in the following manner: If we desire a final mission accuracy of 10μas, clocking-resolution errors will contribute less than 10% to the total error if they are limited to 3μas. At a scanning rate of $540''$/sec, 1μas corresponds to about 5 nsec (=1/clock-frequency). At this resolution and with 34 bits for the time stamp, one can uniquely encode about 85 seconds of mission time. A more complete/lengthy time-stamp could be send down with the 2-D postage stamps where the overhead of extra timing info is much smaller. The exact timing for the 1-D time-stamps can then be easily reconstructed on the ground.

Item numbers 7 and 8 identify the observed star. One can imagine that this ID is not really required since we should be able to reconstruct the star ID with ground-based software on the basis of: 1) scan-rate, 2) CCD-positional, and 3) instrument pointing information. Since the box number varies at a time-scale of $1^\circ/540''/\mathrm{sec} = 6.6$ seconds, we could opt for an intermediate solution where we drop the box number info, but include the identifier within each box[5]. In such a scenario, the total number of bits per star would add up to 192, or 24 bytes, or 1438 star/second or 1.75 times larger than the nominal CSR down-link rate. The overhead over the intensity data is now reduced to 7.2 bits/pixel from 21.6 bits/pixel.

4. Conclusions

- At DLR=822 sec^{-1}, FAME spends 54% of the time in regions where the instantaneous STR exceeds the down-link rate
- In this case, 19% of the total observations are lost

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[4]This item might be included to identify various possible data formats. For example, the 1-D format described here, the equivalent 2-D format, a photometric observation mode with 1 pixel/observation, et cetera.

[5]The maximum number of stars in the USNO-A2 catalog per 1 square degree with $m_R < 15$ mag equals 9384, so that 16 bits are expected to be enough to include even the densest regions down to $m_R \leq 16$ magnitude. Remember that the USNO-A2 catalog suffers from an unknown incompleteness at high stellar densities, and that the details depend on the exact boundaries of the boxes.

- Approximately 35% of observations in the Galactic plane will be lost
- Larger DLRs are easily achieved if the instrument data is stripped of superfluous header information before it is down-linked
- At DLR=1644 sec^{-1}, these numbers decrease to, respectively 18%, 4.2% and 24%
- The maximum instantaneous STR exceeds 12,000 sec^{-1}
- Buffering of 6 10^6 stars is sufficient to eliminate the loss of observations outside GPRs
- The decision to observe or not to observe a target depends on how many targets *follow* shortly thereafter.

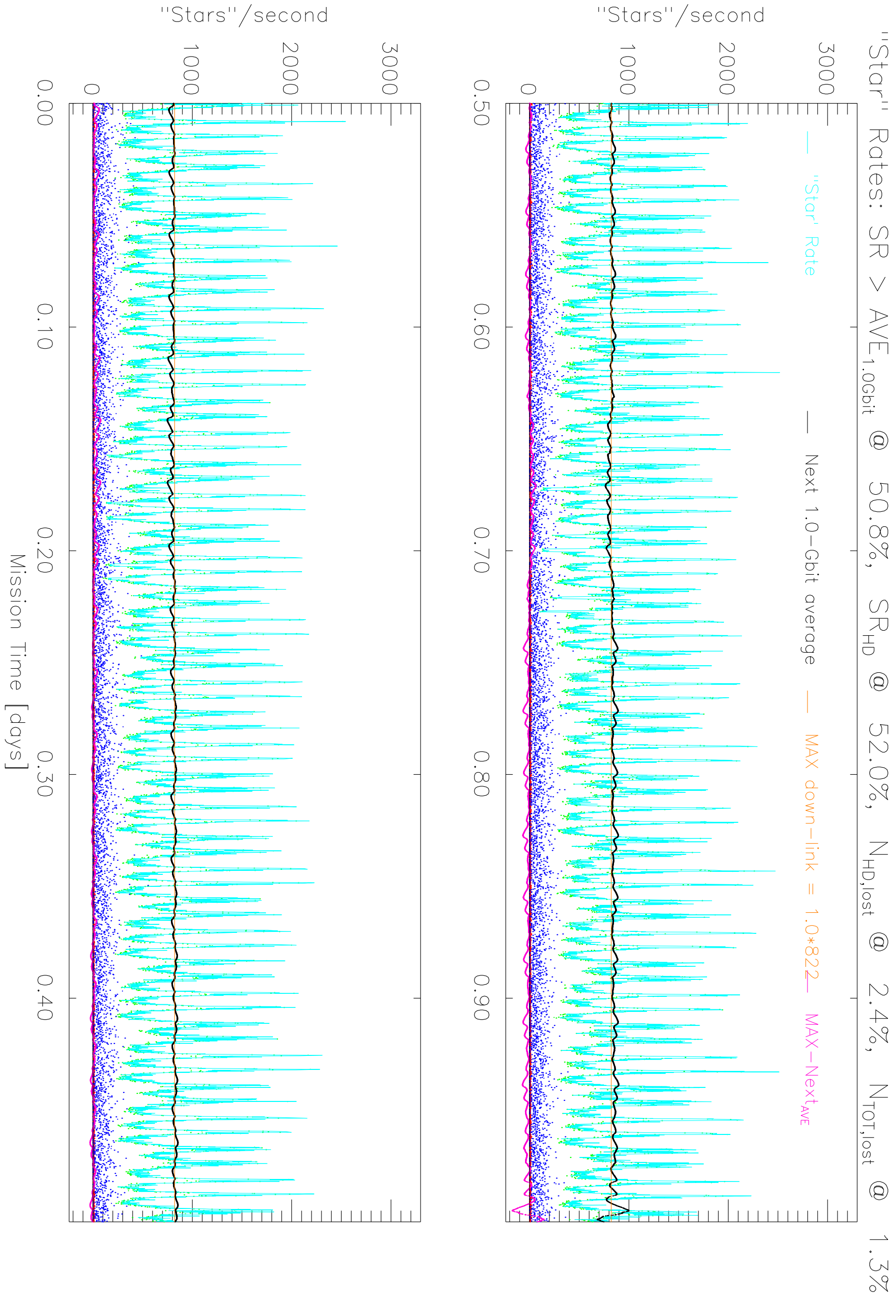

Fig. 1.— The "star" rate during one day of mission time. The red points hovering around 0.0 correspond to the bright-star rate. Multiplying this rate by 20 yields the dark blue points. The cyan, spiky lines represent the sum of the bright stars and the FAME stars. Each spike corresponds to one Galactic plane crossing. The horizontal orange line is the assumed maximum down-link rate, and the wiggly black line the average rate during the time interval that 1 Gbit of data will be accumulated. The wiggly magenta line is the difference between next-1Gbit-average and the maximum data rates.

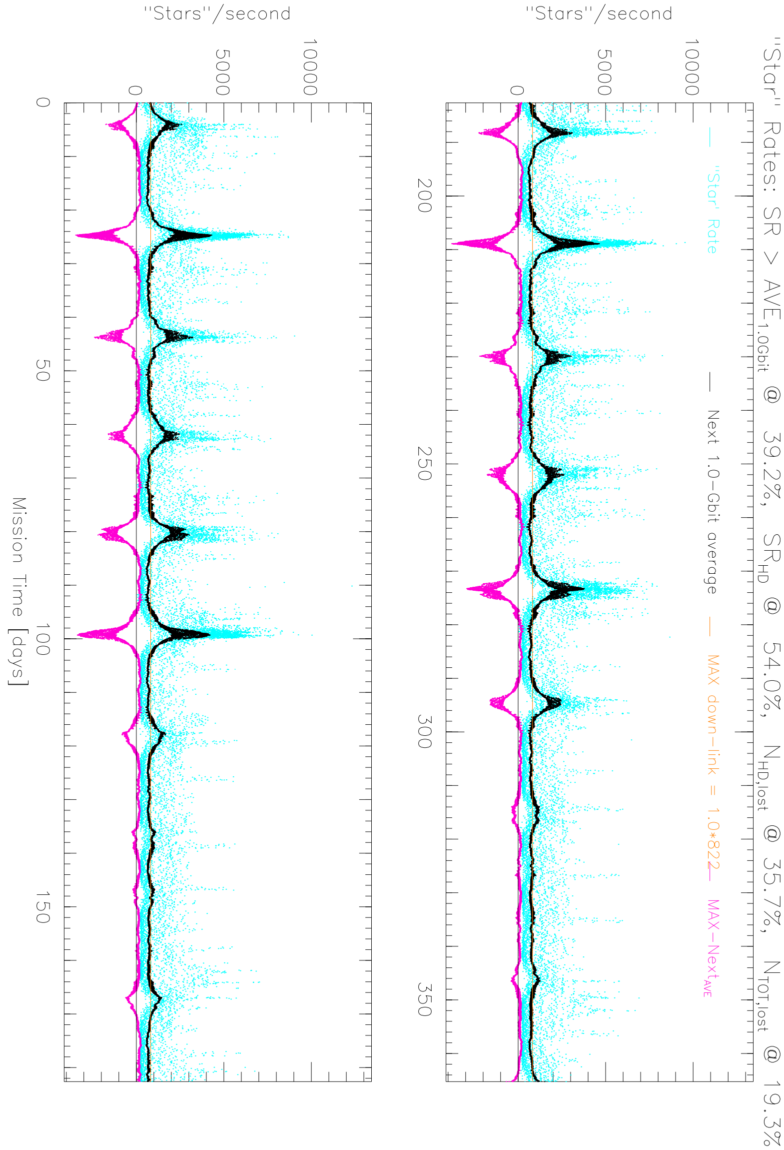

Fig. 2.— Like figure 1, but for 1 year period. Here I do not include the bright stars rate separately. Note that in order to limit the size of the figure, not all data points have been plotted. The fraction of points plotted is large ($\sim$ 1) for large STRs, and decreases to very small values (as little as 1 in several 100) for low STRs. The selection algorithm may introduce some unphysical "striping" at certain STRs. The following plots use the same selection algorithm.

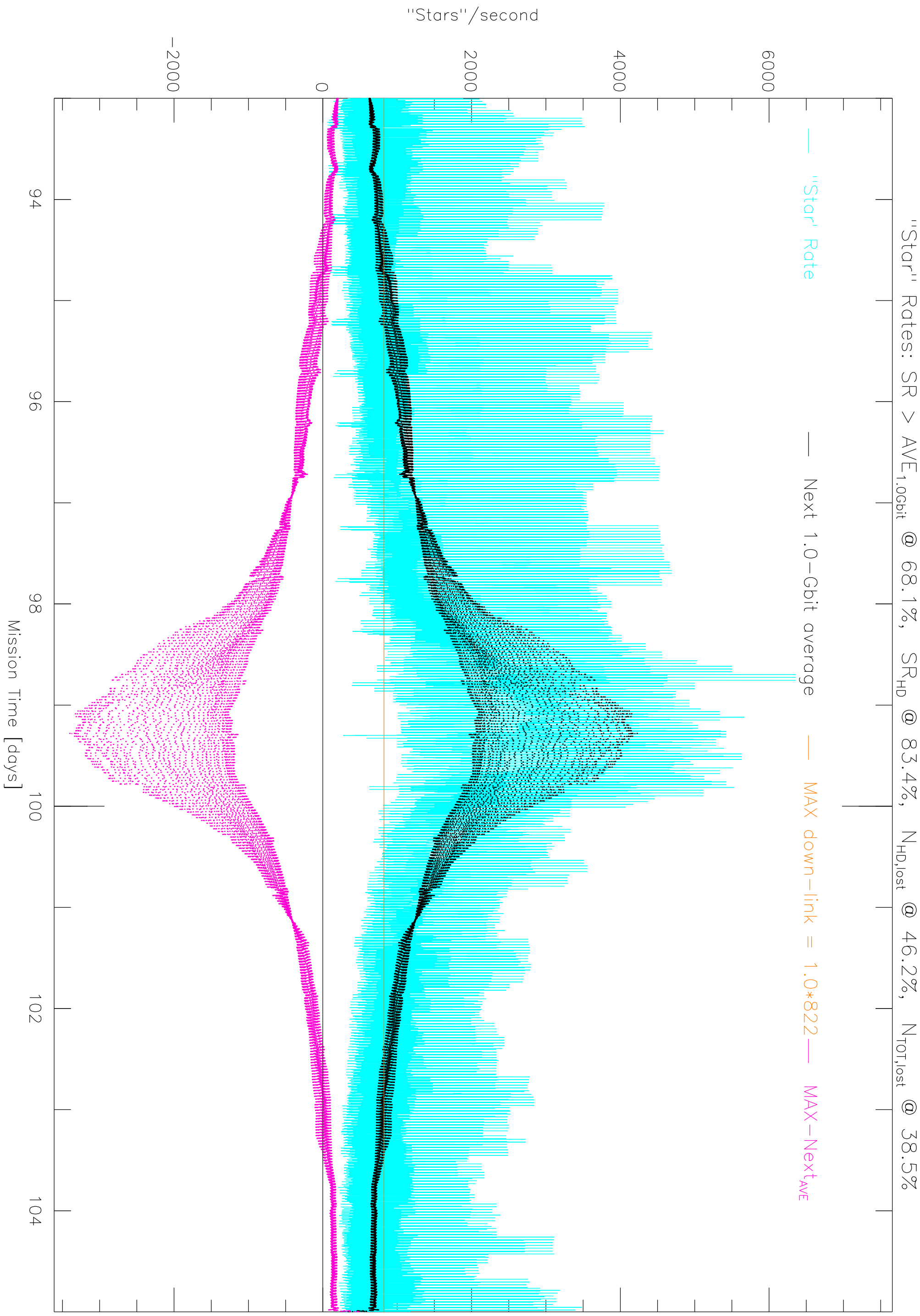

Fig. 3.— Like figure 2, but for the 12 days surrounding day 99, the approximate location of one of the strongest GPRs. The peaks and valley in this plot correspond to crossings of the Galactic "center" and "anti-center", respectively.

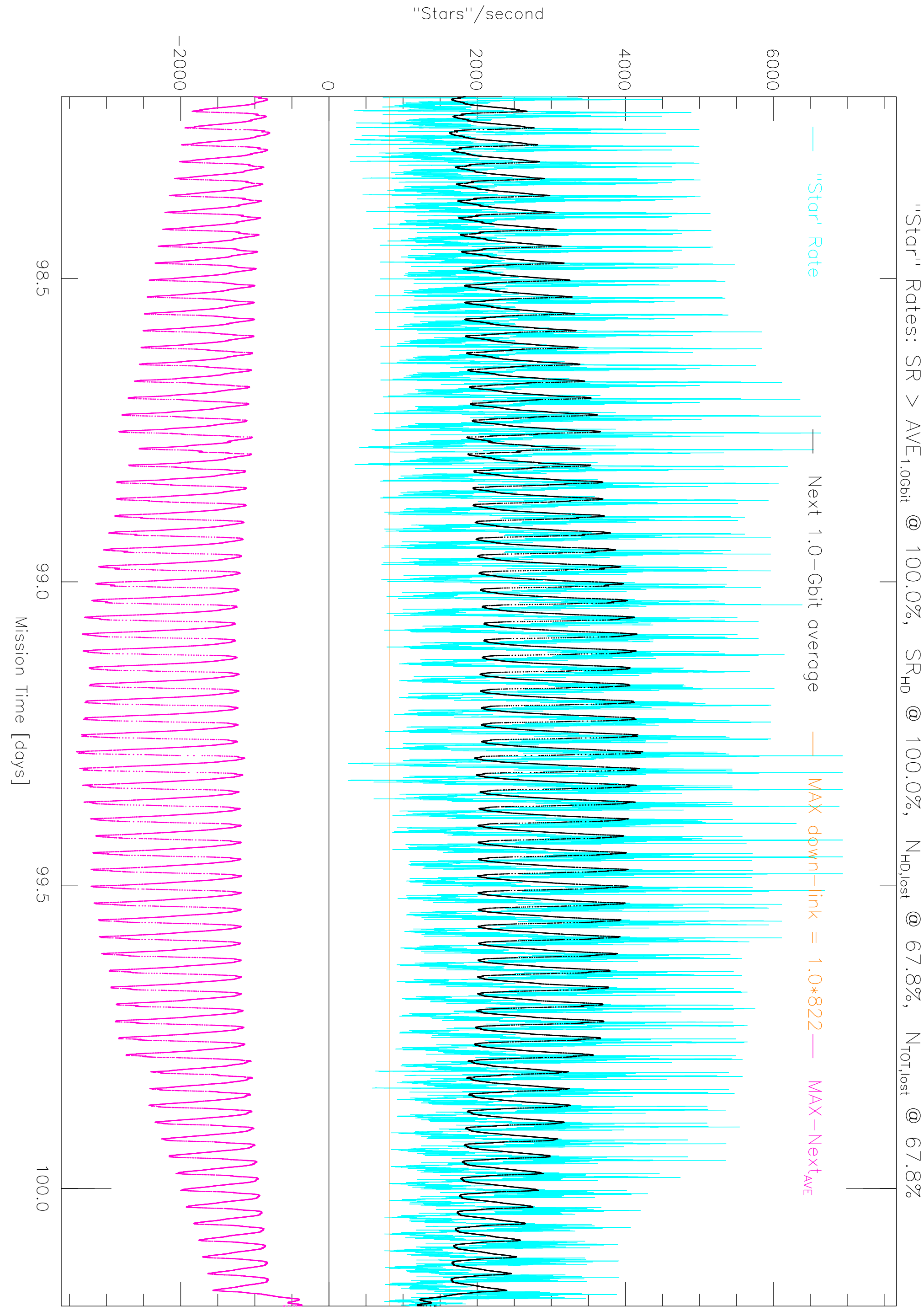

Fig. 4.— Like figure 3, but for the *2 days* surrounding day 99.2, the approximate location of one of the strongest GPRs.

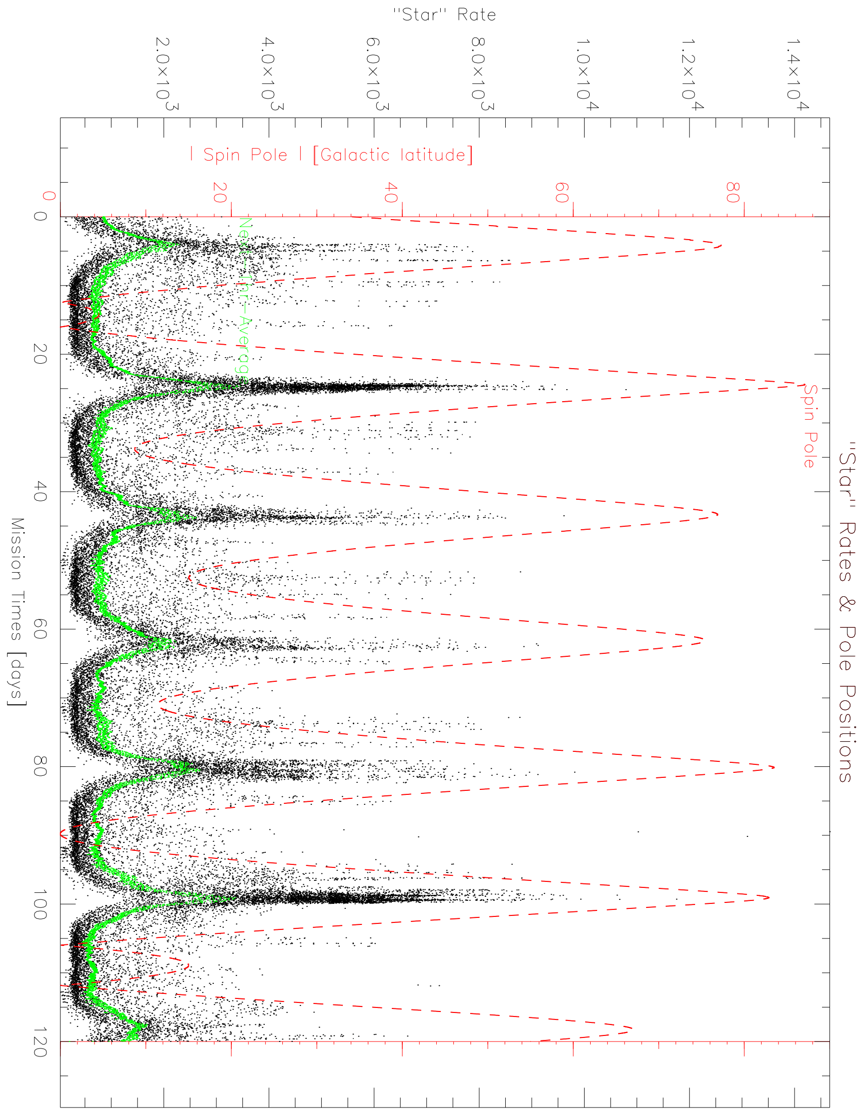

Fig. 5.— The STR for $9 \leq m_R < 15$ stars (black dots) superimposed on the absolute value of the instantaneous position of the pole of the S/C's spin axis (red dotted line, in Galactic coordinates). There is a strong correlation between the pole position and the STR. But note that high STRs also occur away from the pole, and some even when the pole lies exactly in the plane. These must be situations when the S/C rotates through the Galactic 'center.' The next-1-hour average star rate is also plotted (green label and dots).

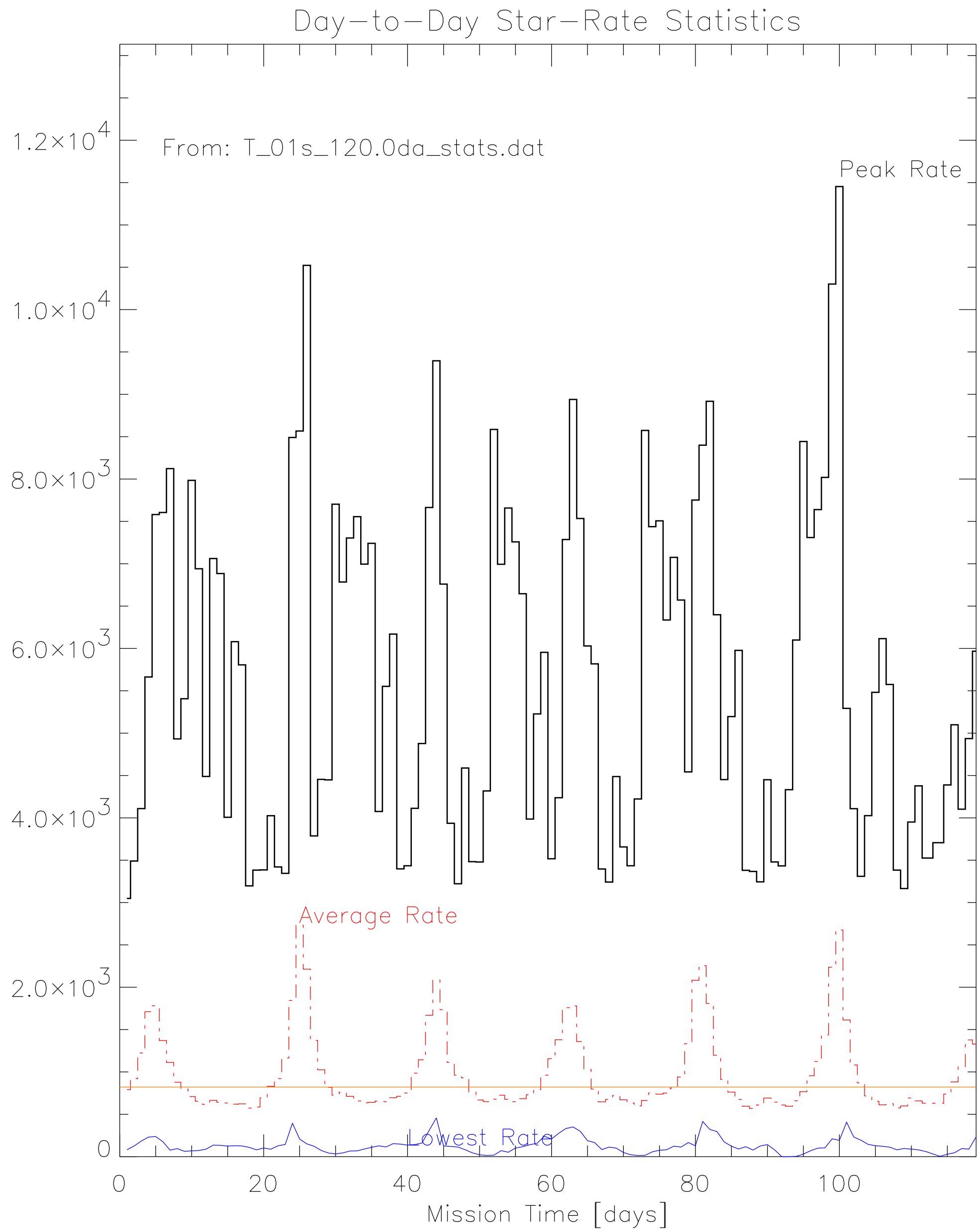

Fig. 6.— The day-by-day binned STR for $9 \leq m_R < 15$ stars calculated for the high-resolution model. The peak values (black histogram) in this high-res model are about twice larger than in the low-res model (cf. fig. 4). The average rate (red dashed histogram) neatly tracks the GPRs (cf. fig 5).